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TEMPERATURE AND STRUCTURE OF THE MOON ACCORDING TO ELECTRICAL CONDUCTIVITY DATA ON ITS INTERIOR

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16. Abstract
Based on the familiar temperature dependence of conductivity, which relates electrical conductivity to parameters characterizing the petrological composition of rocks, a temperature estimate of the lunar interior was obtained: the temperature within the Moon rises sharply from 250° K in the near-surface layer to 800° K at 200 km from the surface and then, beginning from 400 km, tends to its adiabatic value, reaching 1050° K at 600 km. From this interpretation, three major regions of the lunar interiors can be distinguished: 0-200 km, 200-600 km, and the region lying below 600 km (pyroxenitic, peridotitic, and olivinic shells, respectively).

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TEMPERATURE AND STRUCTURE OF THE MOON ACCORDING TO ELECTRICAL CONDUCTIVITY DATA ON ITS INTERIOR

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At the present time, already a number of investigators have /3* obtained the radial distribution of electrical conductivity in the lunar interior [1, 2, 3]. According to their data, electrical conductivity increases from 10^{-8} - 10^{-9} mho at the surface (the conductivity of lunar samples) to 10^{-3} - 10^{-2} mho toward the center of the planet. But its greatest change is observed in the upper mantle of the lunar body, 200 km thick. In addition, in the range of depths 200-400 km from the surface there is a layer (conductive) responsible for a local jump in conductivity on the curve of the total distribution of electrical conductivity within the Moon [1, 2].

An estimate of the temperature conditions of the lunar interior from electrical conductivity data is based on the well-known temperature dependence of conductivity:

$$\sigma = \sum_{i=1}^{3} \sigma_{0i} e^{-\frac{E_i}{kT}}, \qquad (1)$$

where the parameters σ_{0i} and E_i characterize the petrological composition of the rocks, and T is temperature in degrees Kelvin. From this formula is derived the following: to properly estimate the temperature within the planet it is necessary to have a substantiated model of the probable material composition of the Moon. Here one must also bear in mind that the electrical conductivity of rocks is strongly affected, in addition to temperature, also by not only the change in the composition of the /4 rocks as such, but also by their nonstoichiometry, conductive inclusions, phase transitions, and numerous other factors; these effect will naturally be superimposed on the total regularity of the rise in electrical conductivity with increase in temperature

* Numbers in the margin indicate pagination in the foreign text.

and in some manner be reflected in the overall distribution of conductivity within the planet.

Model of material composition and background conductivity. To estimate the effect of factors associated with the internal structure of the Moon, one must calculate the background conductivity, that is, the temperature dependence of the electrical conductivity of the model of the material composition of the lunar interior. The discovery of basalts without an olivinic constituent in the Apollo 11 landing site, and the fact that only slight amounts of olivine are present in the samples of lunar rocks (consisting mainly of pyroxenes and plagioclases) returned to Earth by other spacecraft indicate the substantially pyroxenic composition of the plutonic material, in which the olivine content with depth evidently rises. Since most investigators have concluded that the surface lunar rocks (basalts) are of peridotitic origin, the curve of background conductivity was constructed on the basis of selecting the peridotitic model of the material composition of the Moon, where the olivine content with depth increases to 60-70 percent. In the model, according to seismic data [4], a pyroxenic layer 40 km thick and a bedding depth of 65 km from the surface [4] was taken as the substantially pyroxenic layer underlying the lunar basalt. The transition from this pyroxenic layer to the peridotite takes place, on analogy with the Earth, via olivinic pyroxene. The electrical conductivity values of rocks given in [5] were used for this model, along with contemporary temperature distributions obtained from calculations of the thermal history of the Moon [6]; here it is necessary to /5 note that the minerals of the lunar rocks differ somewhat from the minerals in analogous terrestrial rocks by their composition. Although overall they can be regarded as homogeneous, microanalysis yields a general correlation of a rise in the ferruginous constituent toward the grain boundaries. For example, in clinopyroxenes the content of ferrosilicon at the periphery of crystals reaches 40 mole percent [7], and in olivines the fayalite constituent in the outer zone of minerals varies from 30 to 40 mole percent [8]. In terrestrial conditions this intense ferruginization of the outer zones of minerals is rare. This tendency must lead to the appearance of an overall electrical conductivity of lunar rocks compared with terrestrial. However, with changes in the thermodynamic conditions with depth, the kinetics of mineral grain formation also changes, and where temperatures become high enough (approach the melting point), homogenization occurs, reducing the conductivity of the outer zones of minerals. This in turn is reflected in the electrical conductivity of lunar rocks. A quantitative estimate of this effect must be made on the basis of the familiar L. Landau formula for the conductivity of a statistical mixture with an arbitrary number of phases:

$$\sigma^{1/3} = \sum \theta_i \sigma_i^{1/3}, \qquad (2)$$

where θ_i and σ_i are the bulk content and conductivity of the i-th phase, respectively. The bulk content of the outer zones of minerals is estimated from the measured (using microprobes) distributions of elements along the grains of the latter [7,8]. With this factor taken into account, constructing curves of background conductivity (Fig. 1) showed that the simple change of rocks with which an attempt is made in [1] to account for the local jump in conductivity on the experimental curve does not cause this effect. Here we note only a rise in the electri- /6
cal conductivity with depth. In addition, from the figure it follows that its sharp change in the upper mantle of the Moon is accounted for only by the high temperature gradient in this region.

Interpretation of the local jump in conductivity. Of all the factors associated with the internal structure of the planet and capable of affecting the overall distribution of electrical conductivity, in this study an examination is made of only those factors whose presence on the Moon has either been demonstrated or is sufficiently probable. These include conductive inclusions and phase transitions.

a) <u>Conductive inclusions</u>. From this point of view, the jump in conductivity is accounted for by a local rise in the concentration of a conductive phase at some depth. Its composition includes different kinds of spinellides, ilmenites, oxides, metallic iron, troilite, that is, compounds that for the most part have densities exceeding the density of the intervening silicate rocks [9]. But the Moon is seismically homogeneous in the range of depths 100-800 km from the surface [4, 10]. Therefore, whatever is the mechanism of the local jumplike rise in the concentration of conductive inclusions (conductive phase), its increase must not strongly affect the density of the intervening silicate rocks in this region. Phase markedly affects the density of the latter when its presence exceeds 10-15 weight percent. Therefore its local increase at some depth in the range 100-800 km must not exceed this value. Since the components of the conductive phase are endogenic in origin, and are found in the form of individual inclusions in the samples of lunar rocks, the estimate of its effect on total electrical conductivity must be made either based on the Odelevskiy formula, or the Likhteneker formula, which yield analogous results. According to the calculations, /7 the total electrical conductivity due to this factor rises by three to four times, which lies within the limits of the precision of the determination of lunar conductivity by the methods of electromagnetic sounding. Because of this, this effect will hardly be reflected in the epxerimental curves. Fig. 2 gives a comparison of the experimental curves [1, 2] with the calculated curve (based on the Likhteneker formula). For the latter, the mechanism of the local rise in the concentration of the conductive inclusions consists of the following: Since the constituent phases are endogenic in origin, it can be assumed that during the period of differentiation, along with the basalts nearly all the conductive phase was borne upwards. Therefore, its content with depth up to the foot of the differentiated layer decreases, and increases discontinuously in the sub-foot layer.

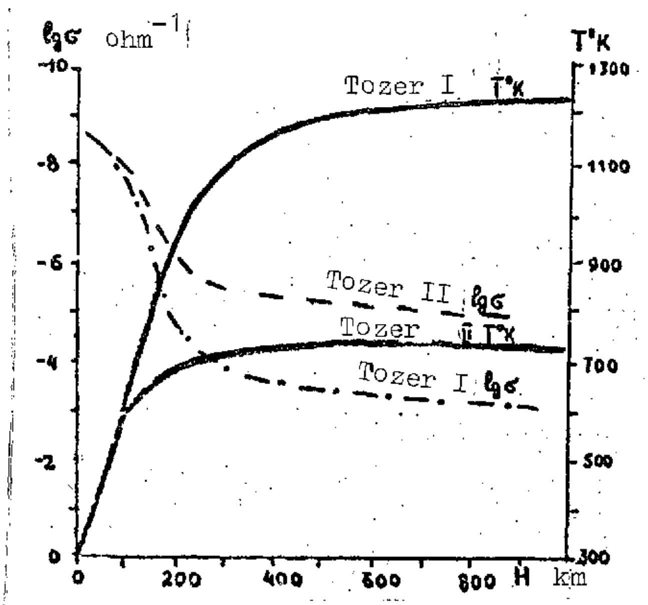

Fig. 1. Calculated curves of background conductivity of peridotite model of the Moon for two temperature distributions after Tozer

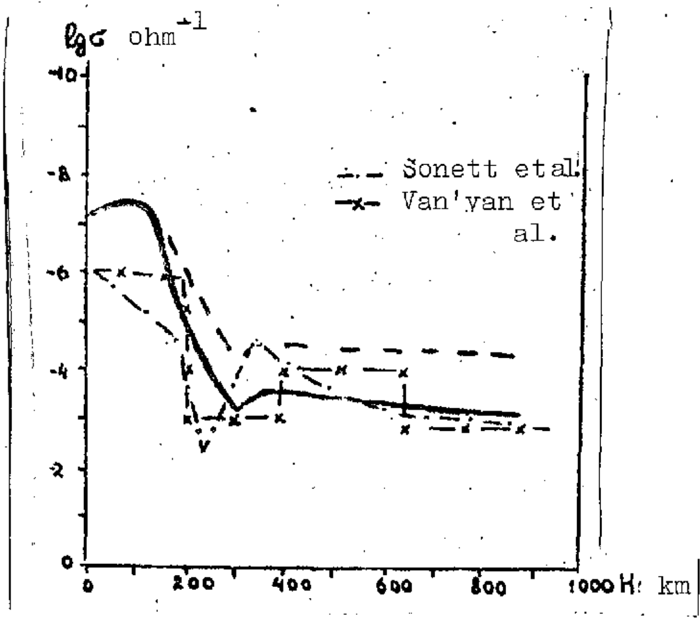

Fig. 2. Effect of conductive phase on general distribution of electrical conductivity in the lunar interior

b) Phase transition. Let us look at the effect of a phase transition. From all the petrological analyses it follows that lunar rocks are basic and ultrabasic rocks and, moreover, at the surface they are spinel-containing rocks, that is, they include compounds such as ulvospinel (Fe_2TiO_4), chromite ($FeCr_2O_4$), hercynite ($FeAl_2O_4$), spinel ($MgAl_2O_4$), and several others.

In terrestrial conditions, these rocks are unstable, and with increasing depth, for strictly specific P-T conditions the spinel-granite phase transition occurs in these rocks. The pressures at which this phase transition can be observed are comparable with the distribution of pressures within the Moon. Both spinel- and granite-containing rocks of the peridotitic type have a density that is nearly the same as the density of the Moon,aas for planets as a whole, and in its seismic chracteristic the spinel-granite transition in the range of depths 100-800 km will not be reflected. All this indicates that this phase transition in the lunar interior is highly probable, all the more so because there is a report [11] that granite was found in one of the lunar samples. And since spinel-containing rocks are marked by higher conductivity compared with granite-containing rocks of the same type, the boundary of the phase transition must be manifested by a jump in conductivity. Since this transition occurs under strictly specific P-T conditions, it can serve (for known composition) as an additional indicator of temperature, on which -- in turn -- depends the magnitude of the jump in conductivity. Thus, in peridotites, with rise in temperature not only is a shift in the phase equilibrium with depth observed, but also a rise in the magnitude of the jump. For example, at 700° K this jump is 0.6 order of magnitude, but at 1220° K it rises to two orders of magnitude. These values lie above the limits of the precision of determination of the electrical conductivity of the lunar interior based on magnetic measurements, and therefore the effect of the spinel-granite phase transition must necessarily be reflected in the electromagnetic sounding curves. Fig. 3 presents for sake of comparison the experimental curve [2] and the calculated curves with allowance for the phase transition, obtained for temperature distributions after Tozer [6]. As can be seen from the figure, the qualitative nature of the change in conductivity with depth is the same. This indicates that if the Moon at depths below 200 km is peridotitic in composition, the spinel-granite phase transition is the most probable explanation of the jump in conductivity on the curves [1, 2]. /8

Estimate of temperature of the lunar interior. The first determinations of the temperature of the lunar interior from electrical conductivity data were made by Sonett et al. [1] and by Dyal and Parkin [3]. In these studies, the petrological basis /9 was either a homogeneous model of the planet, with peridotitic or basaltic composition [3], or a two-layer model of the Moon (not including the basaltic crust), where the peridotitic mantle

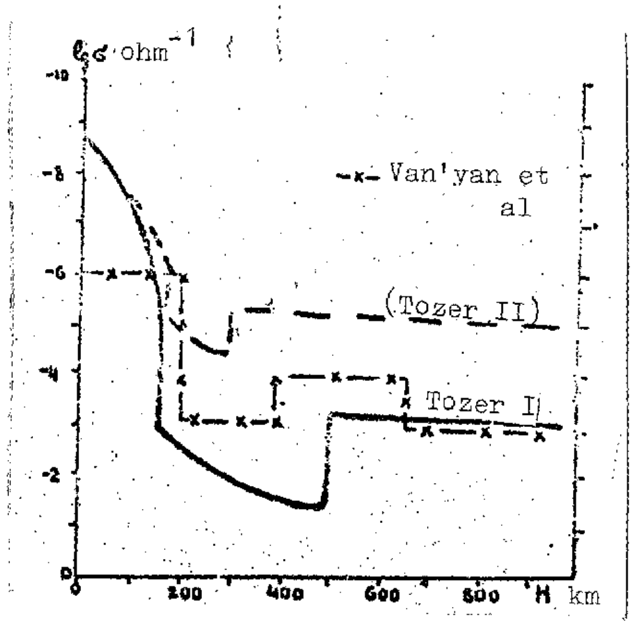

Fig. 3. Theoretical curves of the distribution of electrical conductivity in the lunar interior with reference to the phase transition spinel-granite

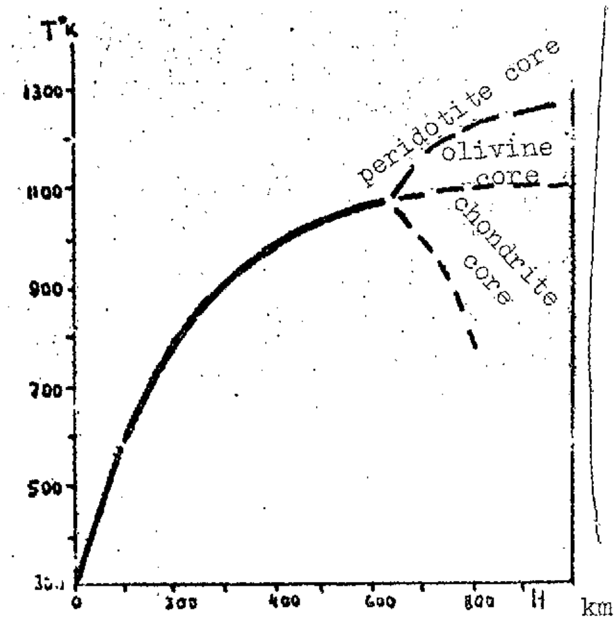

Fig. 4. Estimate of the contemporary temperature within the Moon from electrical conductivity data

changes into an olivine core at the depth of 300 km [1]. Therefore the estimate of the temperature distribution in these studies are in generally close to each other. In the view of their authors, temperature steadily rises with depth and only at depths of 800–900 km from the surfaces reaches 800° C. This nature of the temperature curve does not correspond to any of the calculated thermal models of the Moon.

Interpolation of the experimental curve [2] between the calculated curves (Fig. 3) gives temperatures of 800, 950, and 1050° K for the depths 200, 400, and 650 km from the surface, respectively. Since the temperature in the near-surface layer of the planet (H = 0.8 km) is -25° C, the temperature in the upper shell (200 km thick) increases by approximately 550–600°. A more detailed characterization of its change in this region based only on present electrical conductivity data cannot be made, owing to the insufficiency of these data.

From the experimental curve it follows that below the depth of 650 km in the lunar interior, a change occurs in the nature of the rise in electrical conductivity. The reason for this may be either temperature, or composition, or both factors together. If it is assumed that the composition remains peridotitic with depth, the temperature distribution appears to be as follows: in the depth range 0-400 km the temperature changes from 250 to 950° K; over the depth range 400-650 it tends toward the adiabatic curve ($T = 1050^{\circ}$ K); then it sharply rises, reaching 1250° K at the depth of 800 km, and deeper (judging from the course of the experimental curve) the temperature again tends toward the adia- /10 batic curve, but now with the values $1300-1350^{\circ}$ K. In other words, in the interior of the planet two regions with different temperature regimes will be observed (0-650 km and below 650 km). On the other hand, if at the depth of 650 km there is a change in composition, the peridotitic composition must be substituted by either olivinic,(olivinite), or chondritic (primordial matter). In the first case the temperature does not substantially change in value with depth and tends toward the adiabatic value ($T \rightarrow 1100^{\circ}$ K), that is, the trend of its variation remains approximately the same as over the 400-650 km region. In the second case, when below 650 km there is primordial matter, the temperature rises sharply and at a depth of approximately 800 km does not exceed 700° K. Interpolation of the curve with allowance for corrections for its plotting [12] gives similar results (Fig. 4). On the basis of modern concepts of planetary evolution, a sufficiently rational explanation cannot be given either for the sharp drop, or for the jumplike rise in temperature in the lunar interior. Therefore, at the present time it is more logical to assume that below 600 km there is a change in the peridotitic composition to olivinic and the temperature at a depth of about 800 km reaches approximately 1100° K. This estimate agrees with the estimate of temperature given in [1], since in both cases the same petrological basis was selected for this depth. However, in the 0-600 km region the estimate of the present-day temperature differs from the previously obtained temperature states on the basis of electrical conductivity of the lunar interior by a factor of 1.3 (Fig. 4). Also, qualitatively this curve does not differ from the present-day distribution of temperature within the planet deriving from the calculations of the thermal models of the Moon, where the convective transfer of heat was taken into account [6] /11 (that is, those models that better reflect the actual thermal history of the Moon than other models). Therefore, it can be stated that several conclusions following from an examination of these models, such as: the radiogenic sources of heat are found in an upper layer of the Moon, of relatively small thickness; heat transfer from the surface of the planet is due to free radiation into outer space; and several other conclusions, are indirectly confirmed by the electrical properties of the lunar interior. By reason of this and on the basis of the analysis made, the temperature estimate is as follows: the temperature within the planet rises sharply from 250° K in the near-surface layer to 800° K at the depth of 200 km from the surface and then, beginning from 400 km, tends to its adiabatic value, reaching 1050° K at the depth of 600 km.

Stratigraphy of the lunar interior. On the basis of the interpretation, it is possible to refine the stratigraphy of the Moon by distinguishing three major regions in it: 0-200 km, 200-600 km, and the region lying below 600 km from the surface (pyroxenitic, peridotitic, and olivinic shells, respectively). The pyroxenitic (upper) shell consists of anorthosite plus basalt (uppermost 65 km), pyroxenite (40 km thick layer) [4], and a transitional layer of olivinic pyroxenite (75÷100 km thick). In the peridotitic (middle) shell, at the depth of 400 km the spinel

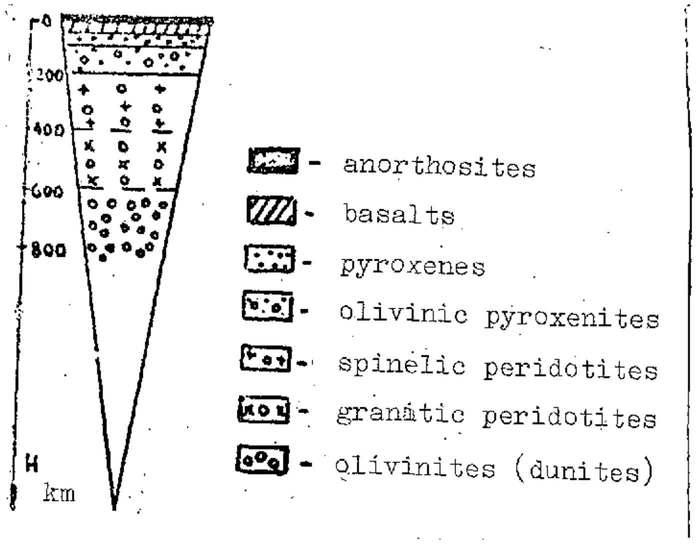

Fig. 5. Stratigraphy of the Moon from its electrical and seismic properties

peridotites are replaced with granitic peridotites by means of a phase transition, which is reflected in the experimental curves of electromagnetic sounding. Thus far it was not possible to stratify the lower shell on the basis of currently available electrical conductivity data (Fig. 5).

REFERENCES

1. Sonett, C. F., Smith, B. F., Calburn, I. C., Schubert, G., Schwartz, K. et al., Nature 230, 350 (1971). /12

2. Van'yan, L. L., Berdichevskiy, M. N., Yegorov, I. V., Krass, M. S., Okulesskiy, B. A., and Fadeyev, V. Ye., "Several principles of the deep probing of the Moon," Paper presented at the 15th General Assembly of the International Association of Geomagnetism and Aeronomy, Moscow, 1971.

3. Dyal, P., and Parkin, C. W., J. Geophys. Res. 76/25 (1971).

4. Toksor, N. N., Press, F. et al., The Moon, Vol. 4, 1970, p. 430.

5. Parkhomenko, E. I., and Bondarenko, A. T., Elektroprovodnost' gornykh porod pri vysokikh temperaturakh /Electrical conductivity of rocks at high temperatures/, Moscow, Nedra Press, 1972.

6. Tozer, D. C., The Moon, Vol. 5, No. 5, 1972.

7. Bence, A. E. et al., Earth Planet. Sci. Let. 8, 193 (1970).

8. Gibb, F. G. F. et al., Earth Planet. Sci. Let. 11, 161 (1971).

9. Haggerty, S. E., Nature, Phys. Sci. 233, 1156 (1971).

10. Toksor, N. N. et al., Science 174, 687 (1970).

11. Trail, R. J. et al., Science 169, 981 (1971).